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TAKE-OFF OF HEAVILY LOADED AIRPLANES

By A. Pröhl

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

TECHNICAL MEMORANDUM NO. 460.

ASSISTING THE TAKE-OFF OF HEAVILY LOADED AIRPLANES.*

By A. Pröhl.

As stated in my treatise, "Take-Off Distance for Airplanes" ("Zeitschrift für Flugtechnik und Motorluftschiffahrt," 1926, pp. 316-322 - for translation, see N.A.C.A. Technical Memorandum No. 381), the take-off distance for many commercial airplanes is very great and, under unfavorable circumstances (heavy loading, poor condition of the ground) often reaches values which are too great for the size of the take-off field. This is especially true of ocean airplanes and in general of airplanes undertaking long nonstop flights, which have to carry exceptionally large quantities of fuel.

In the present article, several suggestions will be made for shortening the otherwise long take-off distance. For the numerical verification of the process, I will use a graphic method, proposed by Professor W. Müller of Dresden,** and also used by H. Herrmann for determining the take-off distance of seaplanes.***

The fundamental dynamic equation, "resultant ^{force} power = mass x acceleration," can be written $R = m \frac{\Delta v}{\Delta t}$ for consideration by

*"Der Start schwer belasteter Flugzeuge" in "Zeitschrift für Flugtechnik und Motorluftschiffahrt," Jan. 28, 1928, pp. 25-30.

**"Betriebswissenschaftliche Untersuchungen von Bahnanlagen" in "Verkehrstechnische Woche," 1926, p. 440.

***Schwimmer und Flugbootkörper," 1926 Yearbook of the "Wissenschaftliche Gesellschaft für Luftfahrt" (See N.A.C.A. Technical Memorandum No. 426, for translation).

zones. Then $\frac{R}{\Delta v} = \frac{m}{\Delta t}$, which is constant for a constant time interval of about 2 seconds. Hence it is also possible to represent the ratio $R/\Delta v$ by straight lines (of constant angle of inclination γ) in a power-speed diagram, in which every such straight line refers to the constant time interval. In the following example, the mass $m = 700$ kg (1543 lb.), $\Delta t = 2$ seconds, and hence $R/\Delta v = 350$ kg sec/m.

We accordingly plot curves for the drag and driving power against the speed (Fig. 1). Curve I is the ground resistance or friction, which decreases with the speed, due to the development of lift. Curve II represents the air resistance and is plotted from I down (total drag W). Curve S represents the propeller thrust. The area between the curves S and W represents, in its ordinates, the forces R available for acceleration according to the above equation. Hence, if we draw, with like angles of inclination $\tan \gamma = \frac{R}{\Delta v}$ from the origin A_0 , a series of triangles with equally inclined sides, then every succeeding lower apex represents the speed increase attained in the double time interval $2 \Delta t$ (here 4 sec.). The number of zigzag lines of these triangles then represents half the take-off time. The take-off distance can be found by a second diagram (Fig. 1b), by drawing lines in Figure 1a from the pole P to the power axis at the points A_1, A_2 , etc. between the lower apexes of the speed intervals. In the time-distance diagram (Fig. 1b), in which equal time intervals are marked on the axis of the ordinates,

parallels are then drawn to the pole rays, which in their succession yield the time-distance diagram of the take-off run and enable the reading of the take-off distance from a suitable scale on the axis of the abscissas.

Figure 1 represents the take-off of a heavy airplane under ordinary conditions, i.e., under its own power without external assistance. The basic data are as follows:

Take-off weight 7000 kg (15432 lb.);

Engine power 3 x 200 HP. = 600 HP.;

Take-off speed 40 m/s (131 ft./sec.);

Maximum flight speed 45 m/s (148 ft./sec.).

The bench thrust for every propeller^{was}/calculated by equation (14) in my abovementioned treatise (N.A.C.A. Technical Memorandum No. 381, Page 9) ($D = 3$ m, $L_0 = 0.8 \times 75 \times 200$)

$$S_0 = \sqrt{\frac{\gamma}{2g}} \pi D^2 L_0^2 \sim 650 \text{ kg (1433 lb.)},$$

or about 2000 kg (4409 lb.) for all three together. With increasing speed, S will decrease until at $v_{\max} = 45$ m/s (148 ft./sec.), the thrust just eliminates the prevailing resistance. The resistance or drag line I (ground friction) begins with $0.08 G = 560$ kg (1235 lb.) for $v = 0$ and falls parabolically to 0 at the take-off speed of 40 m/s (131 ft./sec.), an allowance of 70 kg (154 lb.) being made for the small initial friction of the tail skid. The air resistance, curve II, corresponds to a gliding angle of $1/8$ (at v_{\max}) at 880 kg (1940 lb.)

and from that point toward $v = 0$ it likewise falls parabolically to 0.*

In a recent article, in which similar relations of seaplanes are discussed, Professor Hoff makes some remarkable observations.** He shows how the selection of the propeller should be made from the standpoints of efficiency and the position of its maximum on the speed curve. Hoff calls attention to the fact that, with reference to the take-off conditions, it may be necessary to use propellers somewhat less favorable for flying than others, which would not, however, enable taking off from the water. Similar conditions also occur with heavily loaded land airplanes. If, however, the take-off is facilitated by artificial means (whereby no such critical condition develops as in the case of a seaplane), this precaution is no longer necessary, and the best propeller for flying can be used. Of course, under such circumstances, the same holds true for seaplanes. If the thrust is increased by the measures proposed below (especially proposal 4 in logical extension to the take-off from water) and so far as possible in the domain of the critical speed, the choice of the best flying propeller would then need to be made only from the standpoint of the best flight conditions.

For the airplanes under consideration the power loading at

*In this example the take-off distance is 808 m (2651 ft.) and the take-off time 34 sec. ($8\frac{1}{2}$ triangles!)

**"Das Grossflugboot" in "Werft, ~~Reederei~~ und Hafen," 1927.

the beginning of flight is exceptionally high, and the take-off distance would therefore be excessively long. It is absolutely necessary to reduce it, which can be done only by increasing the take-off power, on the one hand, and artificial lightening of the airplane on the other hand. The first way leads to the use of a supplementary power which must, however, satisfy the following conditions.

1. It must be of considerable magnitude;
2. It must act not simply at the beginning, but during the whole take-off and especially at the higher speeds;
3. It must not be accompanied by any considerable permanent load increment;
4. It must develop no excessive stresses;
5. Complexity of the driving mechanism must be avoided as much as possible.

The simplest way would naturally be to greatly increase the engine power for a short time. This leads to overdimensioned and supercharged engines, to which "altitude gas" is given during the brief take-off period, thus increasing their power in a way similar to that employed in high-altitude flight. For this purpose, the propellers should have adjustable blades capable of developing very great thrust at the beginning of the take-off. Since gasoline is the lightest source of power, such a method is the simplest in any case. This method was used in the seaplane races in Venice for the Schneider Cup, where it increased the

power 50-70%, though with fixed propeller blades. Condition 4, however, opposes this method and must be heeded for ocean airplanes in particular, because it greatly reduces the chances of the engine holding out for a long voyage.

Another method would be the accumulation of energy by running the engine longer before the start. Theoretically, it may be concluded that a stationary run of t_1 sec. with N_1 HP., with an accumulation efficiency ζ and with constant loss of N_2 HP. for t_2 sec. during the take-off, yields

$$N_2 = \zeta \frac{t_1}{t_2} N_1$$

as additional power, whereby the take-off distance can be reduced in the ratio $\frac{N}{N + N_2}$.

This idea has often been expressed and was used, for example, in old German patents (Schlie-Hamburg No. 111609 in 1898 and Dr. Hertel and Paul-Bremen No. 302669 in 1913). It is also obvious, since the braking of an airplane engine before the start is an unavoidable, but as yet useless, waste of energy.

The question arises as to how such an accumulation and restoration of energy can best be accomplished and whether it can be made effective during the whole take-off period or during only a portion of it.

The latter question is best answered by Figure 1, from which it is seen, toward the end of the take-off when the speed is already very great and the acceleration very small, that any in-

crease of the latter is especially valuable, for the small zig-zags come closer together in the narrowed acceleration space (Fig. 1a, long duration of this take-off period) and a disproportionately long part of the take-off distance must accordingly be charged to this portion. If the thrust can be increased during this period, it is immediately expressed in larger time triangles and a smaller number, hence in a corresponding reduction of the take-off distance.

Such a thrust increase might also be effected by the use of variable pitch propellers which, even at high speed, would partially prevent the reduction in the thrust which would otherwise occur. Of course it is also desirable to obtain any possible power increase from the accumulated energy. The variable pitch propeller is then given a higher pitch, which enables it to develop a greater torque and consequently to absorb a greater engine power.

The accumulation of energy might be effected in various ways: first mechanically, at least on airplanes, where this method would chiefly come into question, through a flywheel driven at a very high speed. In our example, with about 65 kg (143 lb.) weight and 80 cm (31.5 in.) diameter, it could be brought to 10,000 R.P.M. by means of a 600 HP. aviation engine, with the aid of a hydraulic transmission gear, during the accumulation period.* If, during the take-off, the R.P.M. of the flywheel is then reduced, within 15 seconds, from 10,000 to 1500 (like-

*For the sake of comparison with the other cases, only a single engine (instead of 3×200 HP.) will here be assumed.

wise with interposition of the variable transmission gear), about 200 HP. can thus be taken from the flywheel, disregarding the losses. This additional power could very well be used in conjunction with the engine power for driving the propeller with a considerably greater pitch and it would be the pilot's task to suitably regulate the transmission and the variable pitch propeller during the brief take-off period. The greatest difficulty in connection with this method would probably be the construction of a suitable transmission gear, which must be flexible enough to allow the flywheel to continue to run quietly after the manner of a free wheel with some reduction in the driving force during the accumulation period and, on the other hand, to enable the regulation of the torque with respect to the power transmitted at the time.*

Moreover, such a driving gear g with its flywheel S (Fig. 2) would be useful in gliding flight, in order to hold in constant reserve an excess power which would be available for any emergency. Any device of this kind, as already mentioned, would probably come into question only for one-engine airplanes. Transferred to our example, however, where, at the end of the take-off period, it enables an increase of as much as 25% in the thrust for 12 seconds, it could effect a considerable shortening

* When, for example, in this new method of accumulation, the engine is also once throttled. This accumulating is done with the flattest possible adjustment (minimum pitch) of the propeller blades, so that the engine power can be mostly absorbed by the driving gear.

of the take-off period and distance, namely, 4 seconds and 680 m (2231 ft.) according to Figure 3.

The weight of such a mechanism would hardly exceed 150 kg (331 lb.) in the above example of a one-engine airplane, including the heavy variable pitch propeller, which would be only about 2% of the weight of the airplane. This would displace fuel for flying about one hour. This device would therefore be used principally for heavy commercial airplanes on short flights with small fields for taking off.

Another way is afforded by the reaction jet propeller, which has already been used with some degree of success with the high speed toward the end of the take-off period. In order, however, to insure a good result, neither air nor gas alone but a jet of water is projected backward at a very high velocity by explosions of gasoline vapor, in a way resembling that employed in the well-known Humphrey gas pump. A simple calculation shows that, even in this way an appreciable supplementary thrust is attainable.

Assuming that the take-off speed, already attained, is 20 m/s (65.6 ft./sec.) and that, by the combustion of the gas mixture in the explosion chamber at a mean gauge pressure of 5 atmospheres, a stream of water of 200 cm² (31 sq.in.) cross section is projected backward from a water tank in the airplane with a relative velocity of $\sqrt{2g \times 50} = 31$ m/s (102 ft./sec.),

the reaction force is then

$$\frac{0.02 \times 31 \times 1000}{9.81} (31 - 20) = 680 \text{ kg (1499 lb.)}.$$

In order to maintain the effect for at least 4 seconds, 2750 kg (6063 lb.) of water must be projected and hence carried at the start. Furthermore, the initial gauge pressure of 5 atm. must not simply be maintained, but must be increased toward the end (with the increasing speed). This could be accomplished with the aid of an adjustable reduction valve, when the total pressure, produced by the intermittent combustion of the mixture of gasoline and air, reaches a much greater gauge pressure, say of 10 atm. The whole mechanism might be installed under the fuselage and then dropped after emptying.

Of course this device also has serious disadvantages, namely, the weight of the water tank and the weight of the water which, in our example, together amount to about a third of the full load during the first part of the take-off period. This increases the ground friction and lengthens the first part of the take-off distance. However, when Figure 4 is considered, it shows an elevation of the S line, as well as of the W line. The consideration of the time triangles shows a preponderating advantage with respect to the shortening of the take-off (29.5 sec., $S = 700 \text{ m (2397 ft.)}$), which is dearly bought, however, by the complexity and by the need of the room for other purposes. (This method could probably be used more advantageously on sea-planes. No water would then need to be carried but, at the

proper time, water could be taken in through a suitable device and, as in the case of the abovementioned gas pump, be projected backward and downward by explosive pressure. It would probably produce the best results to start this process in the vicinity of the critical condition.)

Here also belongs the attempt to lessen the air resistance or drag of the airplane by removing the boundary layer of air from the wings by suction (See N.A.C.A. Technical Memorandum No. 395). Since the air resistance is appreciable during the last part of the take-off run, some degree of success by this method may be expected if the suction can be applied to the whole wing according to the Prandtl method. The requisite negative pressure might be produced before the start during the accumulation period by the engine, by a rotary air pump with a correspondingly large vacuum chamber. The requisite vacuum can also be obtained by an outside pump before the start. The air container might be so installed that it could be dropped after the take-off. If a lessening of the air-resistance (or drag) coefficients c_w to c_{w1} is attainable, the total drag in the ratio $\frac{c_{w1} + c_w'}{c_w + c_w'}$ is thus reduced, which gives, in our example according to Prandtl's data ($c_w = 0.029$, $c_{w1} = 0.014$ and with $c_w' \sim 0.03$), at best 25% total reduction in the value of W , which corresponds, during the last 10 seconds of the take-off run, to a shortening of the take-off distance by about 80-90 m (262-295 ft.).

The action of these devices is fundamentally different from the application of external energy during the take-off, a principle which was exemplified in the well-known catapult start. This method, first employed with the old Wright airplanes and recently with American naval airplanes from the deck of ships, can not be used here in this form (gravity or compressed-air propulsion with directional track), because it is applicable only to light airplanes for very short take-off distances. For land airplanes, it will probably be possible, however, to invent devices capable of affording help for a long distance. If we should restrict ourselves to a single take-off direction (fixed track) corresponding to the prevailing wind, we might use a motor car on rails, which would be able to exert a great pushing force on the landing gear and even to maintain this force at the greater speed during the second take-off period. Such an expensive installation would naturally be made only where there are regular or very frequent take-offs of heavy transoceanic airplanes.

The conditions for a 20,000 kg (44,092 lb.) airplane may be estimated as follows. The total take-off distance should not exceed 750 m (2460 ft.). At its end, the speed would be 30 m/s (98 ft./sec. or 67 mi./hr.), and the mean acceleration would be 0.6 m/s (1.97 ft./sec.). The inertia drag of 1200 kg (2645 lb.) and the initial friction drag of 1500 kg (3307 lb.) would accordingly require an initial force of 2700 kg (5952 lb.), about 2/3 of which would have to be furnished by the propellers and 1/3

by the starting car. This would require an adhesion weight (axle load) of 4000-5000 kg (8818-11,023 lb.). On the other hand, the engine would have to furnish an additional force of 750 kg (1653 lb.) at the maximum speed, i.e., the starting car should be able to develop at least 300 HP.

A simpler and better method would be to use two starting cars driven by air propellers to tow the airplane. Here no heavy adhesion weight would be required for overcoming the thrust, and the take-off direction could be varied at will, if the aviation field were broad enough. The specially built simple starting cars (motor tricycles with an air propeller and a rear steering wheel) run laterally and ahead of the airplane and assist the latter through towing cables attached to the outer hubs of the landing wheels. Since, during the taxiing, the conditions of motion for the starting cars are the same as for the airplane (up to the lacking lift), they also enable a supplementary thrust according to the power of the engines and a consequent shortening of the take-off distance. The simply constructed starting cars might perhaps be used as tractors for other purposes.

Lastly, the principle of the catapult start might be transferred by a horizontal cable system to the long take-off distance, whereby the starting airplane would be constantly assisted by the pull of the cable. Cable speeds of 20-30 m/s (65.6-98.4 ft./sec.) are not unusual and the requisite loads of not over

1000 kg (2205 lb.) are often several times exceeded by cable engines. In order, however, to save in power and in the first cost of the plant, which would be but infrequently used and only for a few minutes at a time, use might here be made of an efficient mechanism for storing energy, the "Ilgner" system with a weak engine, but a large heavy drum with conically increasing diameter (in order to increase the speed of the cable in spite of decreasing revolution speed) and a cable running over rollers along the take-off path with spring hooks for equalizing the pulling forces. If the cable could be shifted for the different directions of the wind, the results obtained with such a system might be very favorable (take-off time 23 seconds, distance 548 m = 1798 ft.), although always quite expensive (Fig. 5).

Another very simple method for shortening the take-off distance is the utilization of gravity. The older patent literature in the realm of aviation is especially rich in more or less fantastic proposals for enabling the heavy airplanes of that time to take off. Only a few such proposals, however, were actually put in practice as, for example, the already-mentioned take-off with a falling weight used by the Wright Brothers and Bleriot's starting cable with a catching device for the airplane.

The simplest method is the use of an inclined plane. Recently, at the suggestion of Fokker, Byrd's ocean seaplane "America" was able to reduce the take-off distance to 620 m (2034 ft.) by using an inclined plane 30 m (98.4 ft.) long and

3 m (9.8 ft.) high. According to the "Fokker Bulletin" (1927, Nos. 10-11), this device reduced the take-off distance about 400 m (1312 ft.). Actually, however, a very great mound is necessary, as shown by the following rough calculation based on the law of energy.

The total take-off work consists of the work of overcoming the total resistance and the work of acceleration. The former, with the starting distance s and the nearly constant resistance W_m , in the mean (Fig. 1, line W), is $s W_m$. The latter is $\frac{G}{2g} v_{st}^2$, in which v_{st} is the take-off speed. This work must normally all be done by the engines. If a take-off mound with the height h is used, then the work done by the weight is $G h$ kgm, which shortens the take-off distance. With the mean propeller thrust S_m , we have

$$S_m s + Gh = s W_m + \frac{m}{2} v_{st}^2$$

hence

$$s = \frac{\frac{m}{2} v_{st}^2 - Gh}{S_m - W_m}.$$

With our values ($G = 7000$ kg, $v_{st} = 40$ m/s, $S_m \sim 1350$ kg, $W_m \sim 650$ kg), we have

$$s = \frac{560000 - 7000 h}{1370 - 650} = 800 - 10 h.$$

In order, therefore, to effect any considerable reduction in the take-off distance, h would have to be at least 20-30 m (65.6-98.4 ft.), for which reason the above-quoted shortening of the take-off distance by 400 m (1312 ft.) does not appear

probable. The advantage of a high take-off mound is shown graphically by Figure 6, which corresponds to the take-off profile shown in Figure 7. We recognize the initial diminution of the propeller thrust due to the upward slope of the mound and the subsequent great increase of S in the steep descent at just the point where it is most effective.

It is clearly apparent that the best result is obtained near the end of the take-off distance and it would therefore be very advantageous to locate such an inclined plane with a steep slope toward the end of the take-off course, where, however, in the case of a level field, a corresponding excavation would have to be made so that, on the whole, not much saving would be made in the length of the field. In order to use the excavated earth to advantage, it can be piled up as shown in Figure 7, so that the airplane will first climb the gentle slope while the propeller thrust is still great and where, moreover, it is possible to utilize artificial external aid (gravity catapult) for a short distance. The steep descent then begins after the airplane has already attained considerable speed. After the take-off the airplane can climb steeply enough, so that the length of the excavation can be small. The take-off distance can therefore be best shortened by a suitable combination of simple starting devices (Fig. 6, 25 seconds and 586 m = 1923 ft.).

Very different from the abovementioned methods is the towing of a taking-off airplane by another airplane, a method described

in my previously mentioned article (N.A.C.A. Technical Memorandum No. 381) and which was successfully employed, at least in principle, by Espenlaub and the Kassler Raka Works, for engineless trailing airplanes. Here the ground resistance curve, in particular, is lowered by the supplementary lift (Fig. 8). Also, though to a less degree, the thrust curve appears to be raised, the take-off time and distance being correspondingly reduced to 27 seconds and 632 m (2073 ft.). This method of assisting the take-off, first suggested by myself, was warmly advocated for seaplanes by Professor Hoff, who illustrated its favorable operation by an example similar to the one given by me two years ago. It may now be expected that towing experiments will also be tried for facilitating the take-off of engine-driven airplanes and that they will probably be successful.

In all these proposals, economical questions play only a subordinate role, since their main object is to enable a safe take-off in difficult cases and then within the shortest possible distance. In judging these methods, it must not be forgotten that a head wind is always the most efficacious and economical aid in taking off.

Hence the above-described artificial methods for shortening the take-off are to be considered chiefly as emergency measures. The actual application of one or the other of these proposals will depend mainly on whether, with powerful modern engines

and the shorter take-off already enabled by them, such an artificial method is still worth while, and finally, if this be the case, whether a sufficiently practical solution of these propositions can be found.

Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.

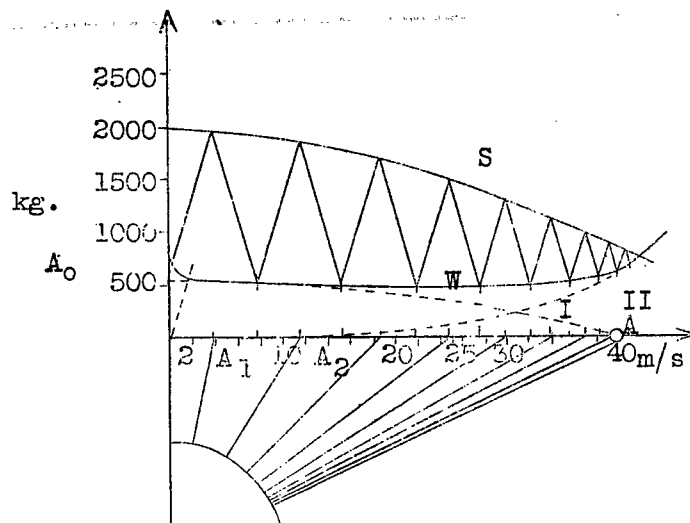


Fig. 1a

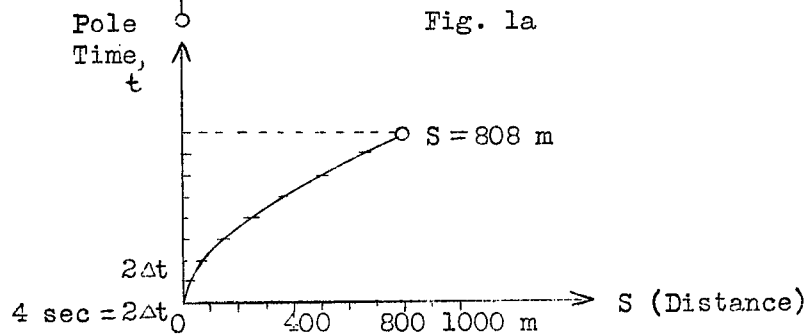


Fig.1b

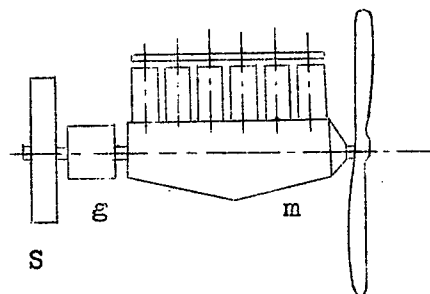


Fig.2.

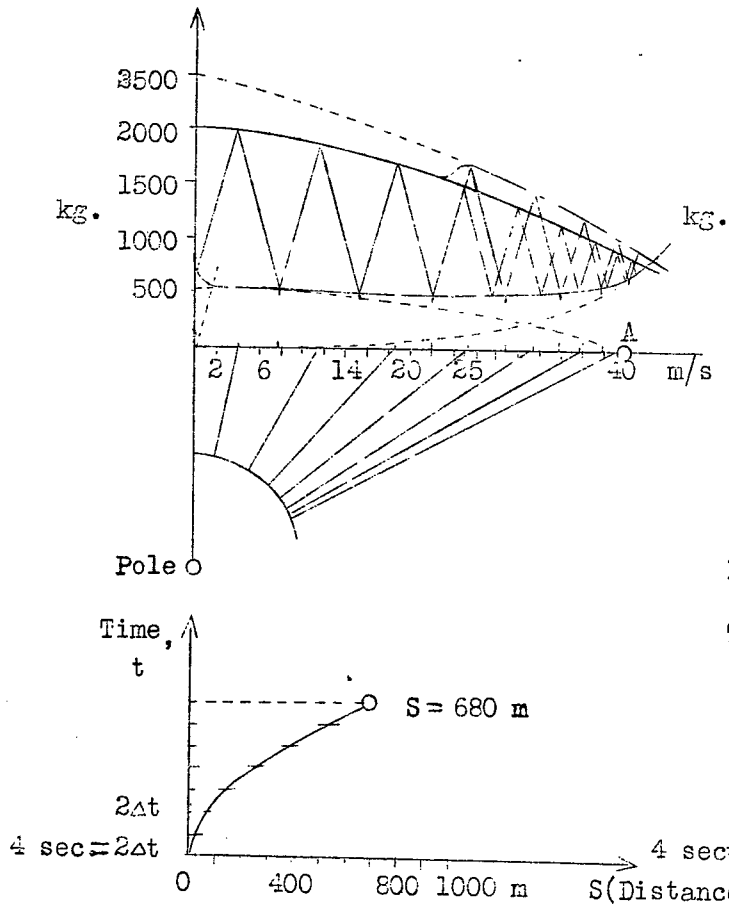


Fig. 3

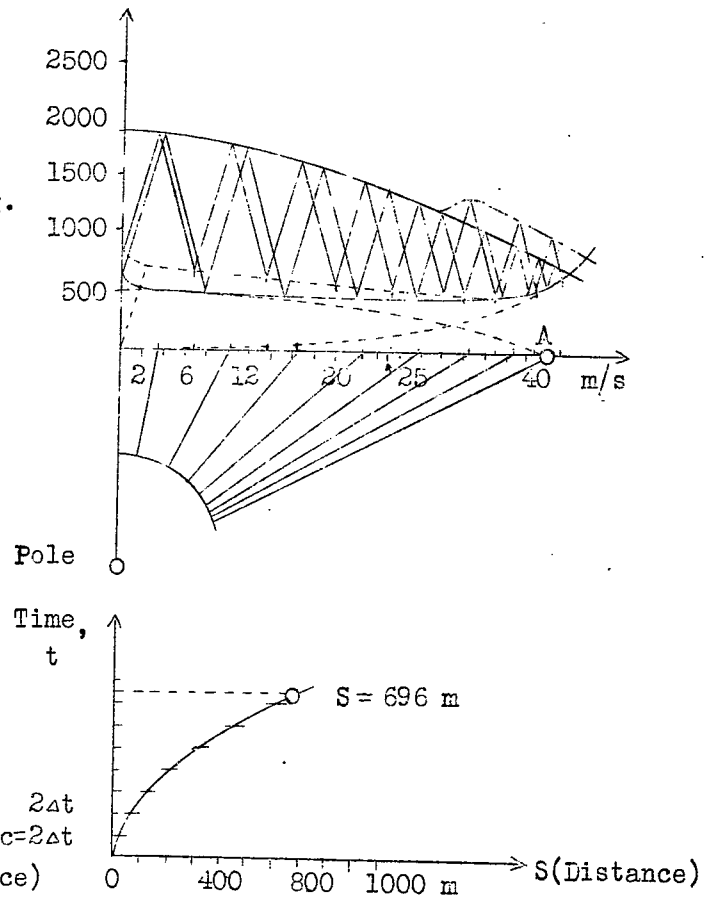


Fig. 4

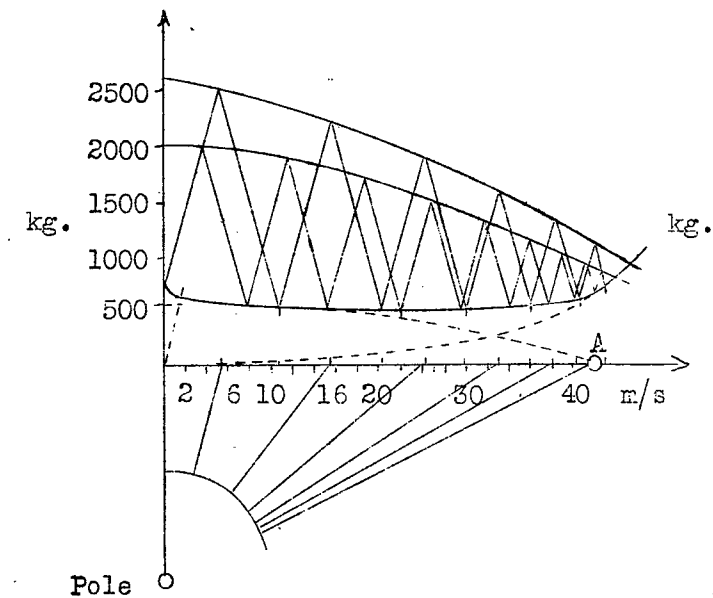


Fig. 5

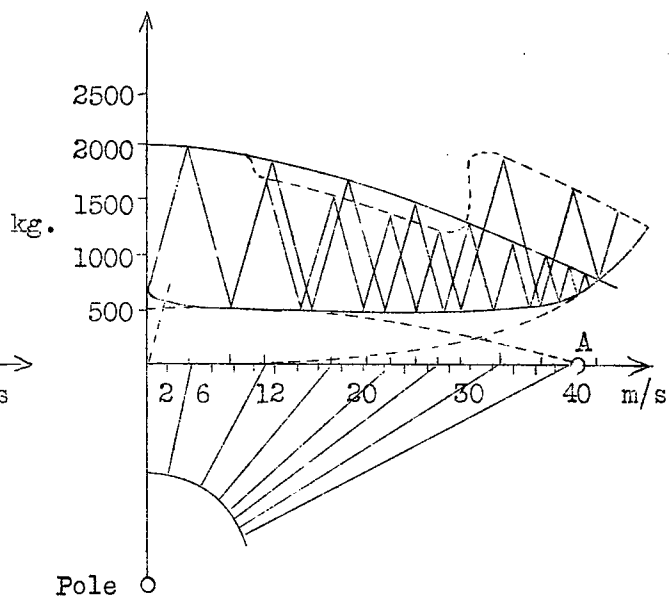


Fig. 6

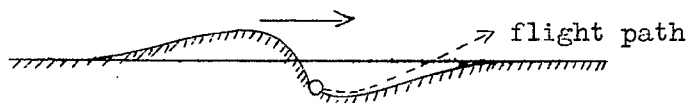


Fig. 7

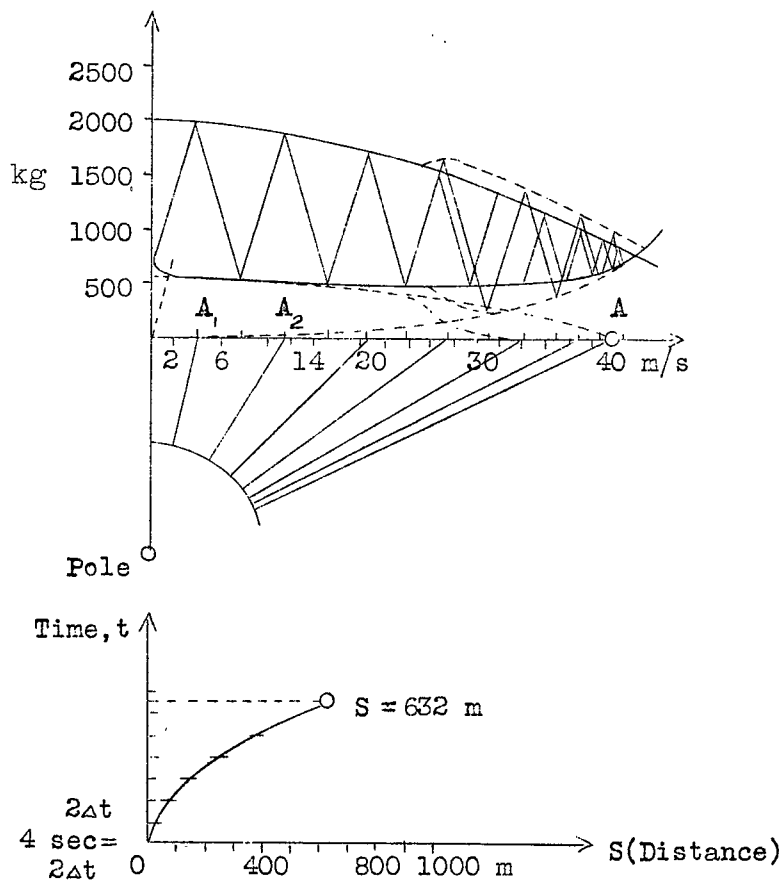


Fig. 8

[illegible]

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